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# LONG-DUCT NACELLE AERODYNAMIC DEVELOPMENT FOR DC-10 DERIVATIVES

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16. Abstract This report presents the results of a wind tunnel test utilizing a 4.7-percent-scale semispan model of the DC-10 in the Calspan 8-foot transonic wind tunnel. The objectives of the test program were to identify the effect of a revised long-duct nacelle shape on the channel velocities, to determine the incremental drag relative to the baseline long-duct nacelle, and to determine channel velocities for the baseline long-duct nacelle and compare them with data obtained at Ames under Contract NAS1-14743. The baseline and the revised long-duct nacelles are representative of a CF6-50 mixed-flow configuration and were evaluated on a model of a proposed DC-10 stretched-fuselage configuration. The results of this investigation showed that the revised long-duct nacelle has an appreciable effect on the inboard channel velocities, resulting in an increased channel Mach number of about $\Delta M_L \approx 0.10$ . However, the pressure recovery on the nacelle afterbody was about the same for both nacelles. The lift curves for both long-duct nacelle configurations were the same. The channel pressures measured at Calspan were in good agreement with those measured at Ames for the baseline long-duct nacelle. The incremental drag for the revised nacelle was measured as two to four counts (three counts is approximately equal to one percent of the airplane drag) higher than that of the baseline long-duct nacelle.					
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## FOREWORD

This document presents the results of a contract study performed by the Douglas Aircraft Company, McDonnell Douglas Corporation, for the National Aeronautics and Space Administration (NASA). The work is part of Phase II of the Energy Efficient Transport (EET) project of the Aircraft Energy Efficiency (ACEE) program, specifically, a portion of the contract "Development and Evaluation of Selected Advanced Aerodynamics and Active Controls Concepts for Commercial Transport Aircraft." The purpose of the study was to investigate the aerodynamic interference drag characteristics of a long-duct nacelle shape revised from that tested in a Phase I EET activity.

The NASA technical monitor for the contract was initially Mr. D. L. Maiden and then Mr. T. G. Gainer of the Energy Efficient Transport Project Office at the Langley Research Center. The support and guidance of Mr. J. R. Tulinius, the on-site NASA representative, are also acknowledged.

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## LIST OF SYMBOLS

All force data presented in this report have been reduced to coefficient form based on trapezoidal wing area. Pressure data have been reduced to coefficient form referenced to freestream pressures. All dimensional values are given in both International Systems of Units (SI) and U.S. Customary Units, with the principal measurements and calculations using the latter.

Coefficients and symbols used herein are defined as follows:

$b_w$	Reference wing span, 256.91 cm (101.14 in.)
$C_D$	Drag coefficient (Drag/ $q_\infty S_w$ )
$\Delta C_D$	Incremental drag coefficient
$C_L$	Lift coefficient (Lift/ $q_\infty S_w$ )
$C_P$	Pressure coefficient ( $P_\ell - P_\infty / q_\infty$ )
$c_w$	Local wing chord, cm (in.)
$M_\infty$	Freestream Mach number
$M_L$	Local Mach number
$P_\ell$	Local static pressure, N/m <sup>2</sup> (lb/ft <sup>2</sup> )
$P_\infty$	Freestream static pressure, N/m <sup>2</sup> (lb/ft <sup>2</sup> )
$q_\infty$	Freestream dynamic pressure, N/m <sup>2</sup> (lb/ft <sup>2</sup> )
$R$	Reynolds number per meter (per foot)
$S_w$	Reference semispan wing area, 0.3855 m <sup>2</sup> (4.150 ft <sup>2</sup> )
$\alpha_F$	Fuselage angle of attack, degrees

## **ACRONYMS**

<b>ACEE</b>	<b>Aircraft Energy Efficiency (Program)</b>
<b>EET</b>	<b>Energy Efficient Transport (Project)</b>
<b>GE</b>	<b>General Electric (Company)</b>
<b>LDN</b>	<b>Long-duct nacelle</b>
<b>SDN</b>	<b>Short-duct nacelle</b>

## SUMMARY

The objectives of the high-speed wind tunnel test program described in this report were to identify the effect of a revised long-duct nacelle (LDN) shape on the wing-pylon-nacelle channel velocities, to determine the incremental drag relative to a baseline LDN previously tested under Contract NAS1-14734, and to determine channel velocities for the baseline LDN and compare them with data obtained from the previous test. The baseline and the revised LDN are representative of a General Electric (GE) CF6-50 mixed-flow configuration. The investigation was conducted in the Calspan 8-foot transonic wind tunnel using a 4.7-percent-scale semispan model of a proposed DC-10 stretched-fuselage configuration. The test was carried out over a Mach number range of 0.60 to 0.84 and over a lift coefficient range up to 0.60 at a constant Reynolds number of  $13.1 \times 10^6$  per meter ( $4.0 \times 10^6$  per foot).

The results of the investigation showed that the revised LDN has an appreciable effect on the channel velocities, resulting in a peak channel Mach number increase of  $\Delta M_L \approx 0.10$  at typical cruise conditions. However, the pressure recovery on the nacelle afterbody was about the same for the revised and the baseline long-duct nacelles. Boundary layer analyses showed that the flow on the revised LDN afterbody was attached. Lift curves for both LDN configurations were the same. The channel pressures measured at Calspan were in agreement with those measured at Ames for the baseline LDN, thus dispelling the concern that the LDN pressures measured at Ames might be optimistic. The incremental drag for the revised LDN was two to four counts higher than for the baseline LDN (three counts is approximately equal to one percent of the airplane drag). While this increment was higher than the estimated value (one count), it may not be completely representative of the true incremental drag, because previous tests in this facility by Douglas have not been successful in determining small drag increments due to configuration changes. The measured drag increment and the increased channel velocities for the revised nacelle shape are of sufficient concern, however, to warrant consideration of pylon or nacelle changes designed to reduce the impact of the revised nacelle shape on the channel velocities coupled with its potential attendant drag increase.



## INTRODUCTION

During Phase I of the Energy Efficient Transport Project under Contract NAS1-14734, a high-speed investigation was conducted in the NASA Ames 11-foot wind tunnel to evaluate the effects of installing a mixed-flow long-duct nacelle (LDN) on the DC-10 (Reference 1). The engine installation used for this investigation was representative of the General Electric (GE) CF6-50, the engine that powers the DC-10-30 intercontinental version. It was concluded that the LDN had very low interference drag, which could be reduced to an insignificant level by adding a small fairing to the current DC-10 pylon shape. The test data also showed that the pressure distributions in the wing-pylon-nacelle channel obtained with a flow-through and a powered nacelle were the same; hence, power effects could be considered negligible.

Following the test of Reference 1, Douglas conducted mixer model tests, the objective of which was to investigate the internal mixer performance. The findings of these tests indicated a requirement for a lower Mach number at the mixing plane and an increased mixing length. For the CF6-50 engine, the mixer requirements translate into an increased nacelle diameter at the mixing plane and a longer nacelle (by 21.4 inches full scale) than the one considered in the Phase I investigation. It was therefore necessary to evaluate the effect of the revised nacelle shape on the wing-pylon-nacelle channel velocities and to measure, if possible, the incremental drag relative to the baseline nacelle of Reference 1.

A second objective of the test related to the differences in the channel velocities measured in the Phase I Ames test for the current production short-duct nacelle compared with the flight data, the latter indicating more severe velocities. Should the difference be valid and also applicable to the LDN, the criticality of the channel velocities for the LDN might be more severe in flight than measured for the model. A suitable adjustment to the pressure data, however, did not appear to invalidate the general conclusion that the interference drag of the LDN was small. In order to explore the concern further, it was proposed to rerun the baseline LDN in the Calspan facility. In this facility, good correlation with flight-measured channel pressure data has previously been obtained. This is probably due to the model installation which removes the tunnel floor boundary layer; at Ames the model was mounted directly on the floor.

The test was conducted in the Calspan 8-foot wind tunnel during November 1979. The model geometry in the area of the nacelle installation was the same as for the DC-10-30 model used in the Phase I investigation at Ames. While Douglas has used this facility extensively for the measurement of airframe loads and pressures, its experience in trying to measure small incremental drag values due to configuration changes has not been satisfactory. Therefore, pressures are used as the primary measurements in this report. While force data are presented, they may not be completely representative.



## LDN CONFIGURATIONS

A comparison of the revised nacelle shape with the baseline LDN is shown in Figure 1. The aerodynamic lines for the revised LDN were developed from findings of Douglas mixer model tests. The tests indicated a requirement for a lower Mach number at the mixing plane and an increased mixing length. For the present investigation, the most expeditious way of satisfying the requirement was to extend the nacelle afterbody rearwards. In this way a larger diameter at the internal mixing plane and a longer nozzle could be obtained. Other solutions to the requirement may be to combine changes to the external and internal duct shapes so that the external shape of the LDN would not be affected as greatly. Such solutions would require careful evaluation of the internal and external performance of the LDN.

The revised LDN model was 2.55 cm (1.01 in.) longer than the baseline nacelle. The geometry was similar to that of the baseline LDN except that the nacelle boattail was given an aft translation. The revised model was a flow-through LDN, because the baseline tests showed that this type could properly represent the pressure distributions in the channel. The pylon was of symmetrical sections streamwise, representing the current DC-10 production shape. No additional pylon fairings were applied.

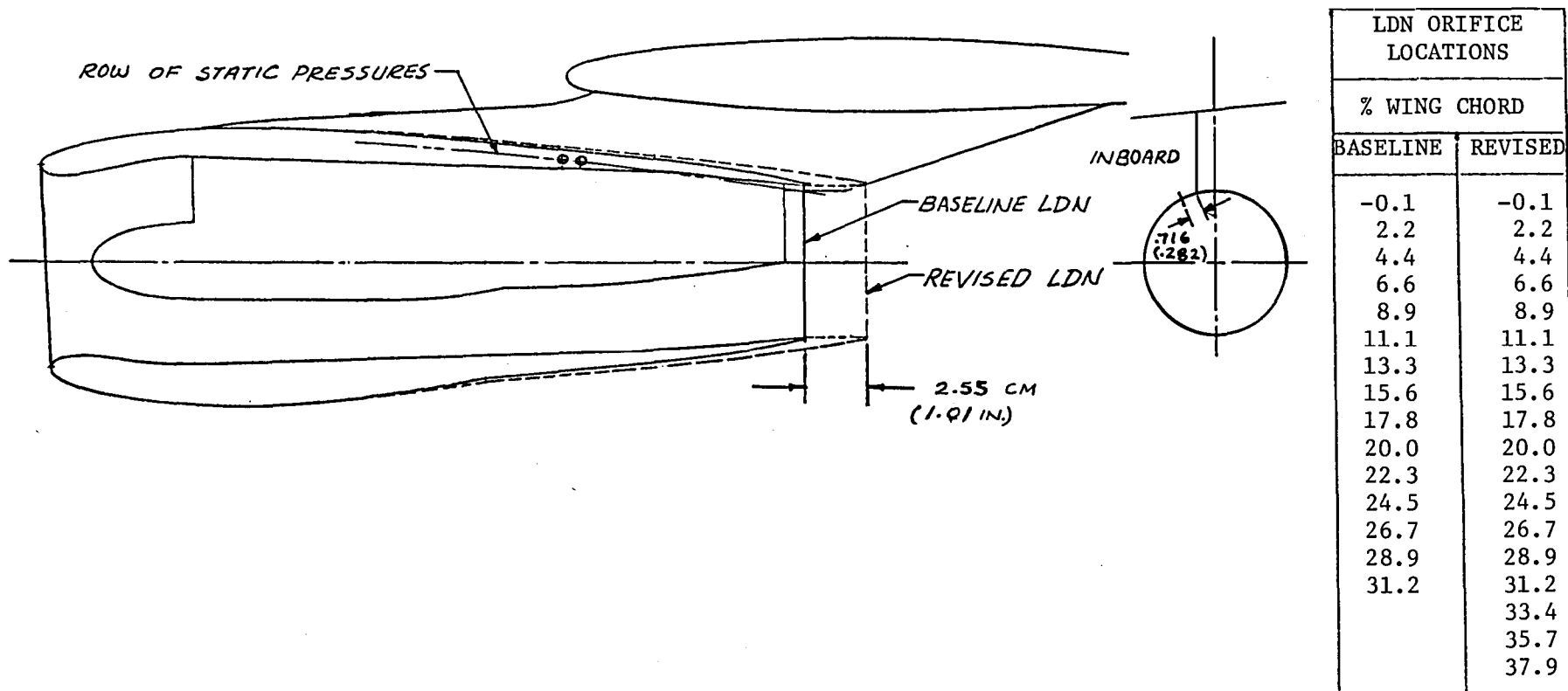


FIGURE 1. COMPARISON OF BASELINE AND REVISED LDN GEOMETRY AND STATIC PRESSURE ORIFICE LOCATIONS

## EXPERIMENTAL APPARATUS AND PROCEDURE

### TEST FACILITY

The test was conducted in the Calspan 8-foot transonic wind tunnel. The tunnel has a perforated throat and an auxiliary pumping system for plenum pumping. The continuous-circuit tunnel is capable of operating from 1/6 to 2-1/2 atmosphere total pressure, thereby providing a wide range of test Reynolds numbers as well as Mach numbers. A more detailed description of this facility is given in Reference 2.

### MODEL DESCRIPTION AND INSTALLATION

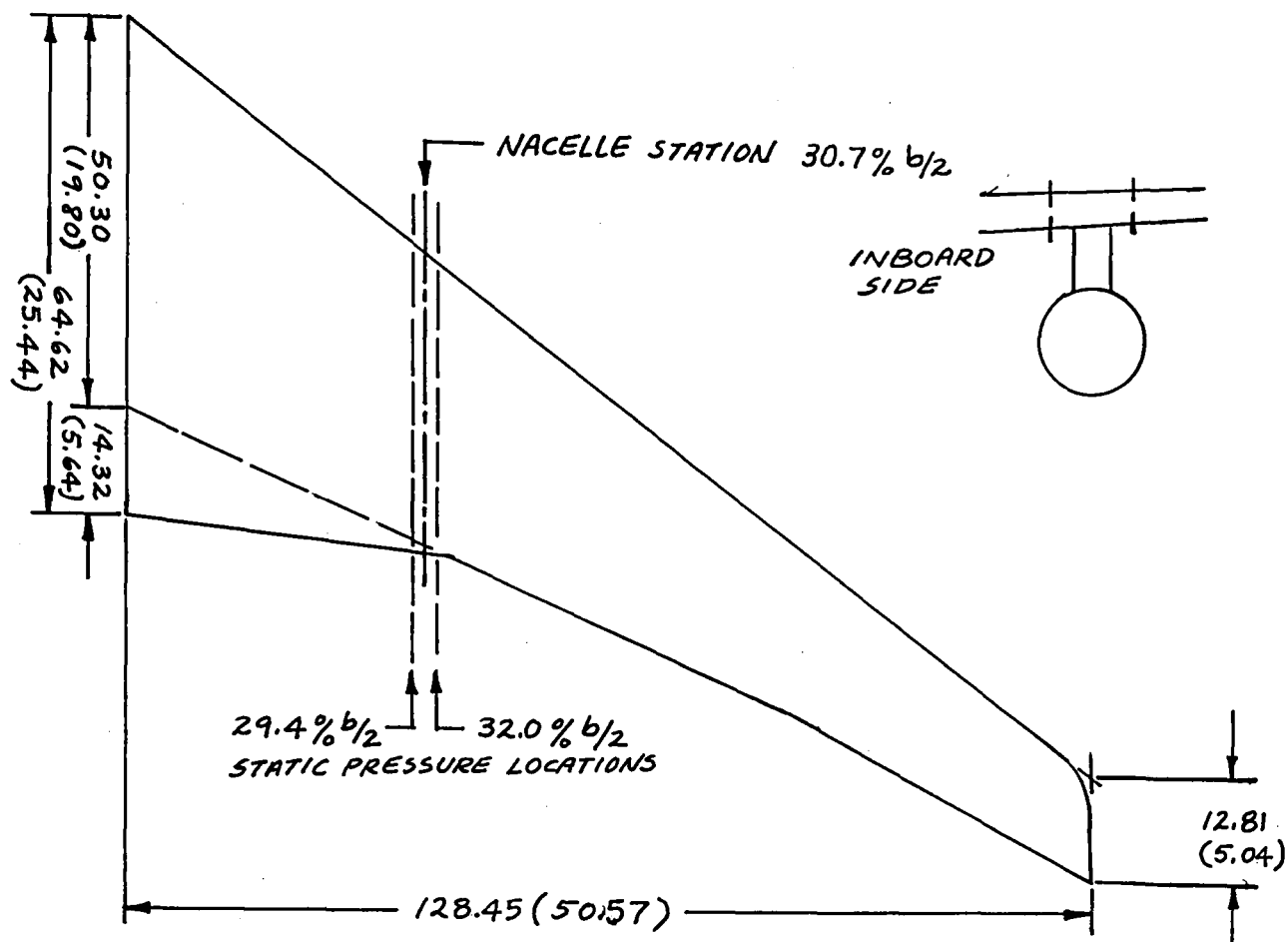
The model used for the investigation was a 4.7-percent-scale semispan configuration representative of the right-hand half of a proposed stretched-fuselage version of the DC-10-30. The differences between this model and the DC-10-30 model used for the Phase I Ames investigation were a 57.3-cm (22.56-in.) fuselage extension, a 10.0-cm (3.95-in.) wing-tip extension, and a 2.75-degree increase in wing root incidence.

The model wing was manufactured to the dihedral and twist representative of a lg loading. The wing geometry and static pressure orifice locations are shown in Figure 2. The wing was instrumented with two rows of pressures on the upper and lower surface at 29.4 and 32 percent of the wing semispan, one on the inboard and the other on the outboard side of the pylon. Both nacelles were instrumented with one row of static orifices on the inboard external surface as shown in Figure 1.

The wing-ylon-nacelle relationship was the same as for the model tested in the Ames 11-foot wind tunnel. A major difference, however, was in the way the model was mounted on the floor. At Calspan the model was mounted off the floor on a splitter plate that removed the tunnel boundary layer, whereas at Ames the model was mounted on the tunnel floor.

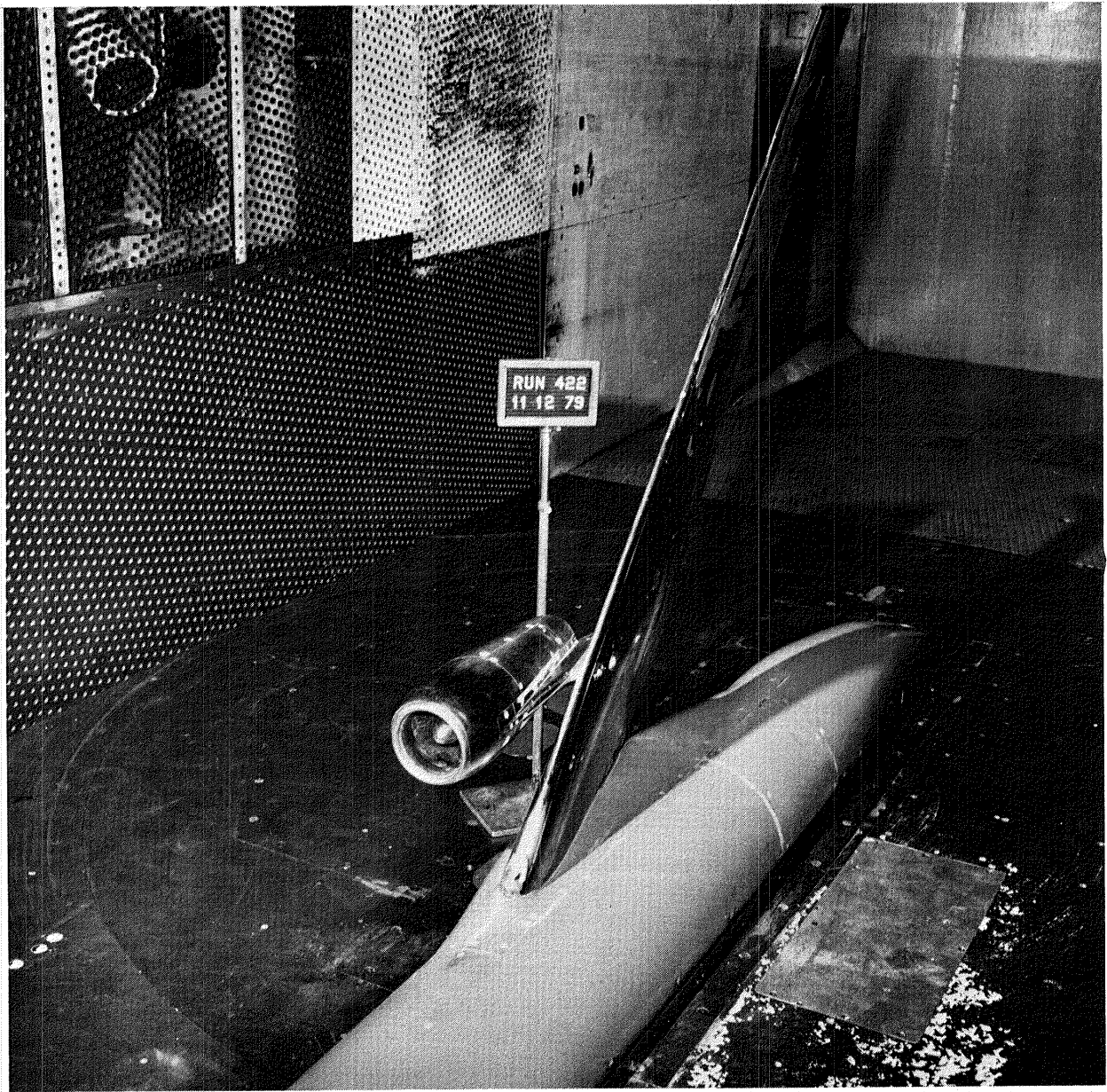
The model was installed in the transonic reflection plane cart and supported by the Calspan RP-5 balance. A splitter plate 6.67 cm (2.63 in.) above the tunnel floor and extending about 63.5 (25.0 in.) forward of the model nose, raised the model above the boundary layer along the floor of the tunnel. An additional nonmetric spacer plate, 1.91 cm (0.75 in.) thick, placed the fuselage plane of symmetry 9.08 cm (3.58 in.) above the tunnel floor, with a 0.51-cm (0.20-in.) gap between the fuselage and spacer to isolate the metric parts from the nonmetric parts. Figure 3 is a photograph of the semispan model with the LDN installed.

All testing was accomplished with transition fixed. Boundary layer transition strips, 0.318-cm (0.125-in.-) wide bands of glass beads, were used on all components of the model. The size and locations of the transition strips on various components of the model were fixed using the criteria described in Reference 3, and were consistent with the procedures used for the baseline investigation at Ames.



ORIFICE LOCATIONS	
% LOCAL CHORD	
L.E.	
0.5	
1.0	
2.5	
5.0	
7.5	
10.0	
12.5	
15.0	
20.0	
25.0	
30.0	
35.0	
40.0	
45.0	
50.0	
60.0	
70.0	
75.0	
80.0	
85.0	
90.0	
95.0	
T.E.	

FIGURE 2. WING GEOMETRY AND STATIC PRESSURE ORIFICE LOCATIONS



**FIGURE 3. SEMISPAN MODEL INSTALLATION IN CALSPAN 8-FOOT TRANSONIC WIND TUNNEL**

## TEST CONDITIONS AND MEASUREMENTS

The test was conducted over a Mach number range of 0.60 to 0.84 at a constant Reynolds number of  $13.1 \times 10^6$  per meter ( $4.0 \times 10^6$  per foot). The angle of attack of the model was varied from  $-1.5$  to  $2.6$  degrees over a range corresponding to lift coefficient values between 0.30 and 0.60 (bounding the cruise conditions).

A four-component external balance was used to obtain the force and moment data during the test. The angle of attack was measured with tunnel turntable readout.

Chordwise static pressure distributions on the wing upper and lower surfaces were measured during the test. Static pressure distributions were also measured on the inboard side of the nacelle.

Data were measured with the wing-fuselage model with and without both nacelle-pylon assemblies. All forces, moments, and pressures were recorded on the Calspan wind tunnel data acquisition system.



## RESULTS AND DISCUSSION

Typical cruise conditions for the intercontinental versions of the DC-10 are 0.82 Mach number and 0.50 lift coefficient. Data comparisons in this report are presented for this lift coefficient. The test configurations were also evaluated at Mach numbers as low as 0.60 to determine the effects of compressibility. Where appropriate, configuration comparisons have been shown as a function of Mach number.

The inboard wing-pylon-nacelle channel pressures are compared for the baseline and revised LDN in Figures 4 through 6. At 0.60 Mach number and 0.50 lift coefficient, the channel flow is subcritical (Figure 4). The suction peak is about  $\Delta C_p = -0.15$  higher across the channel for the revised LDN. The pressure recovery on the nacelle afterbody appears to be about the same for both nacelles. Figure 5 shows that the flow in the channel is characterized by a growth in the peak suction pressures with increasing Mach number. The suction peak for the revised LDN grows in a way similar to that of the baseline LDN. A bad pressure orifice on the wing lower surface prevented direct determination of the suction peak for the baseline LDN, so the Ames data have been used for this purpose. This difficulty did not exist for the revised LDN because the suction peaks occur further aft. The data show that the channel flow becomes critical ( $M_L = 1.0$ ) at a Mach number about 0.04 to 0.05 lower for the revised LDN than for the baseline LDN. Figure 6 shows the complete channel pressure distributions for both nacelles at 0.82 Mach number and 0.50 lift coefficient. The peak local Mach number is 1.2 for the revised LDN, compared with 1.1 for the baseline LDN, and the peak occurs further aft. However, the peak channel Mach number is below the  $M_L = 1.3$  to 1.4 levels which have been previously demonstrated to cause shock-induced nacelle flow separation and an attendant drag penalty (Reference 4).

To further evaluate these data, a boundary layer analysis was conducted using the wind tunnel-measured afterbody pressure distributions for the revised LDN. This analysis did not show any tendency toward flow separation on the revised LDN afterbody. While these results do not suggest a problem, the higher channel velocities are of sufficient magnitude to be a concern, and suggest treatment to lower the peak suction pressures. This treatment could consist of a revision to the nacelle afterbody shaping or to the pylon shape, or a combination of both. Revisions to the shape that affect the internal duct would also require a tradeoff between internal mixing performance and external performance.

Pressure distributions on the outboard wing lower surface with nacelles on and off are shown in Figure 7 at 0.60 and 0.82 Mach numbers and 0.50 lift coefficient. The figure shows that the flow on the outboard wing lower surface is subcritical at the cruise Mach number. This is consistent with past measurements for swept wing aircraft. Because of the wing sweep, the addition of component velocities is not critical on the outboard wing-pylon-nacelle channel. No pressure measurements were made on the outboard side of the nacelle.

A comparison of the airplane lift curves with the baseline and the revised LDN at 0.82 Mach number is shown in Figure 8. The lift curves for both nacelles are essentially the same. At

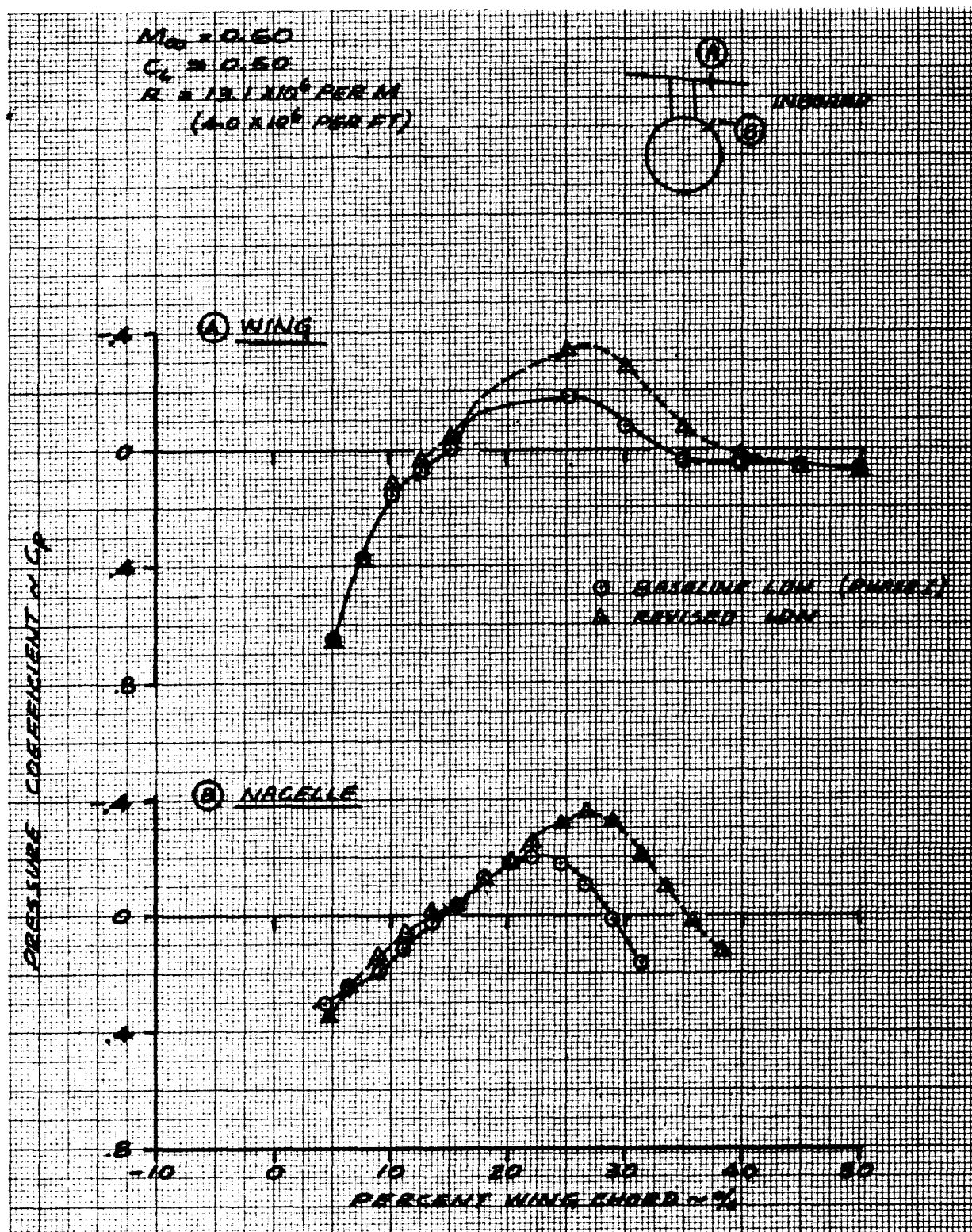


FIGURE 4. EFFECT OF LDN INSTALLATION ON INBOARD CHANNEL PRESSURE – BASELINE AND REVISED LDN ( $M_\infty = 0.60$ ,  $C_L = 0.50$ )

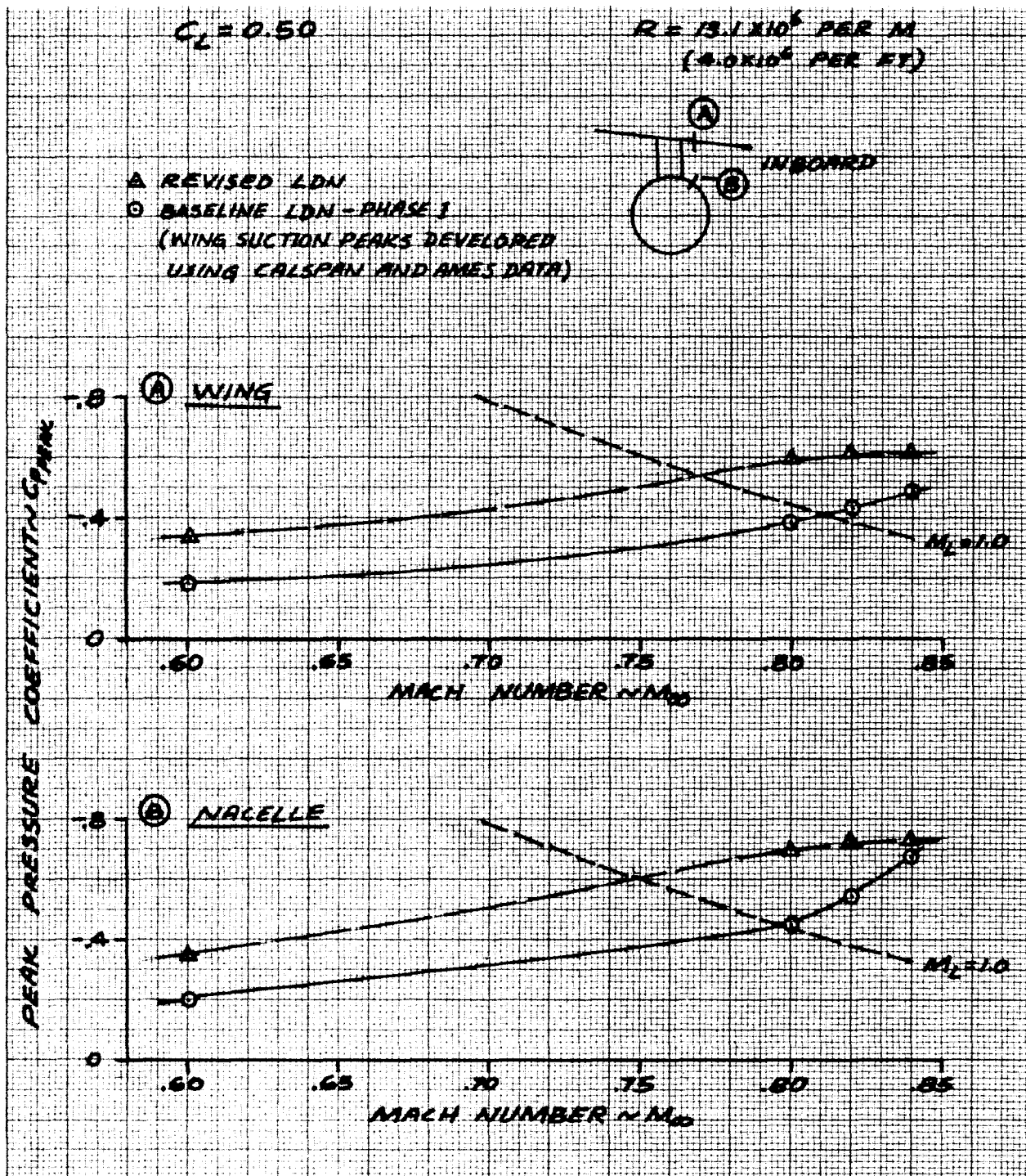


FIGURE 5. EFFECT OF FREESTREAM MACH NUMBER ON INBOARD CHANNEL PEAK SUCTION PRESSURES - LDN WITH SYMMETRICAL PYLON ( $C_L = 0.50$ )

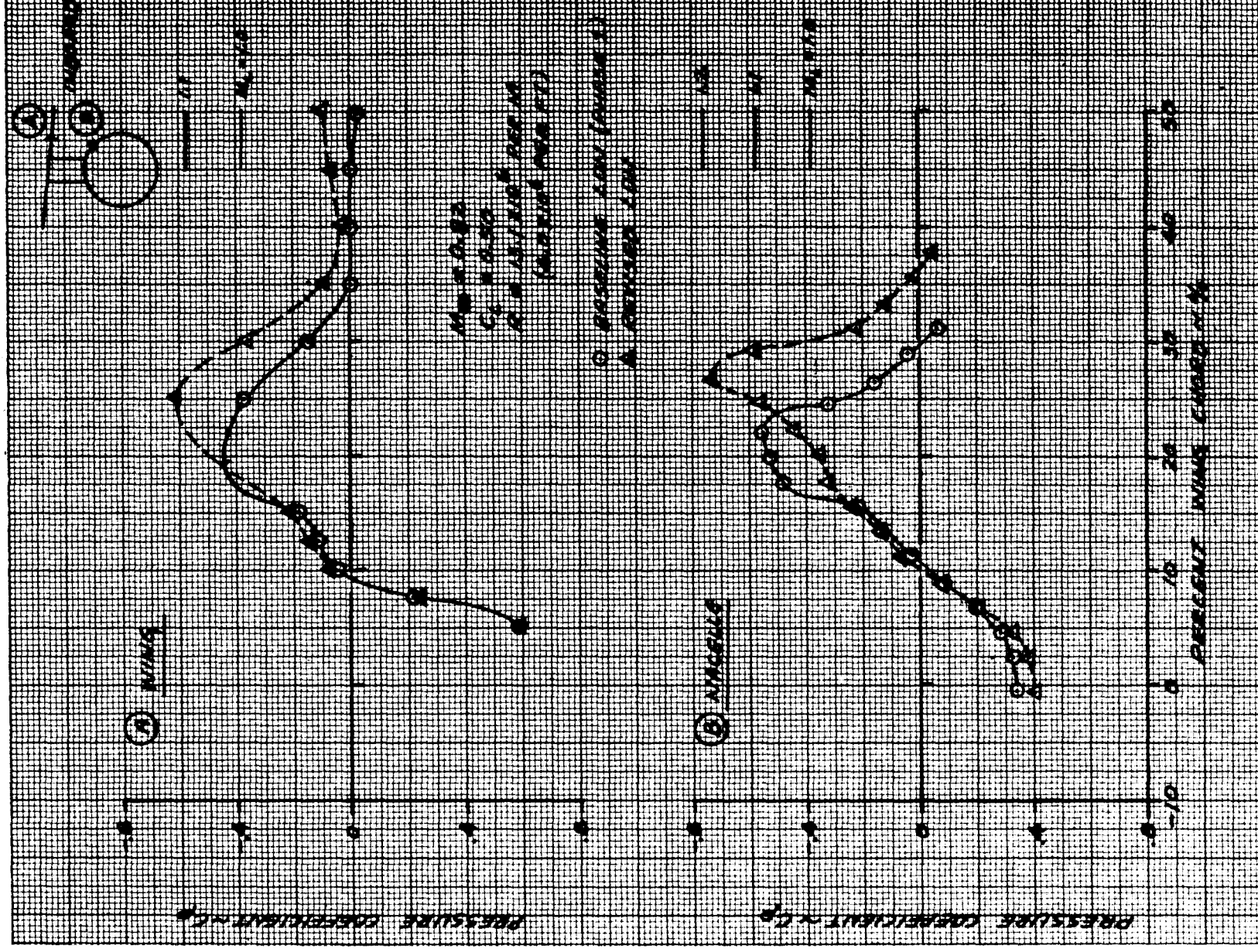


FIGURE 6. EFFECT OF LDN INSTALLATION ON INBOARD CHANNEL PRESSURES - BASELINE AND REVISED LDN ( $M_\infty = 0.82$ ,  $C_L = 0.50$ )

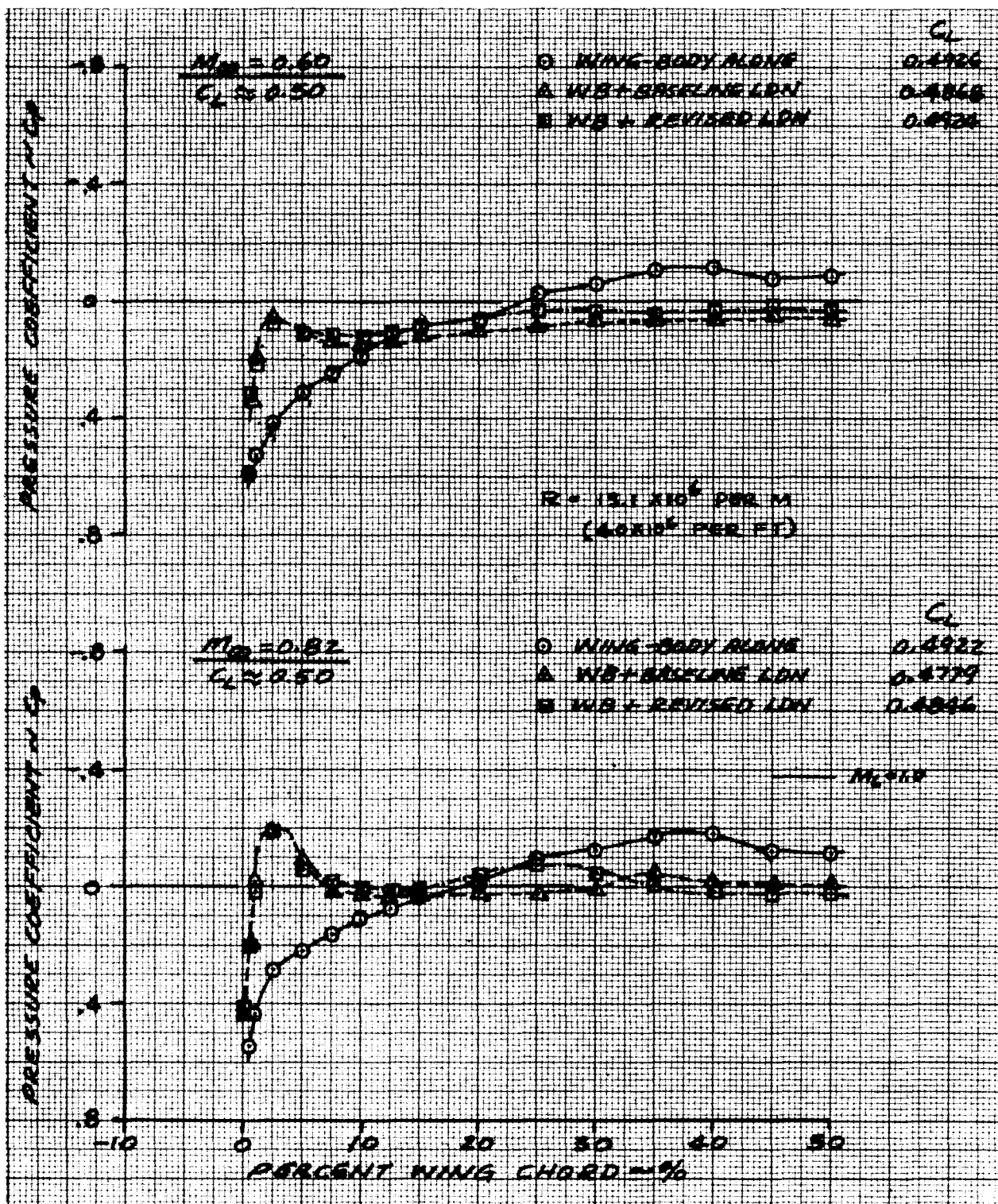


FIGURE 7. EFFECT OF LDN INSTALLATION ON OUTBOARD WING LOWER SURFACE PRESSURES - BASELINE AND REVISED LDN ( $M_{\infty} = 0.60$ ,  $M_{\infty} = 0.82$ ,  $C_L = 0.50$ )

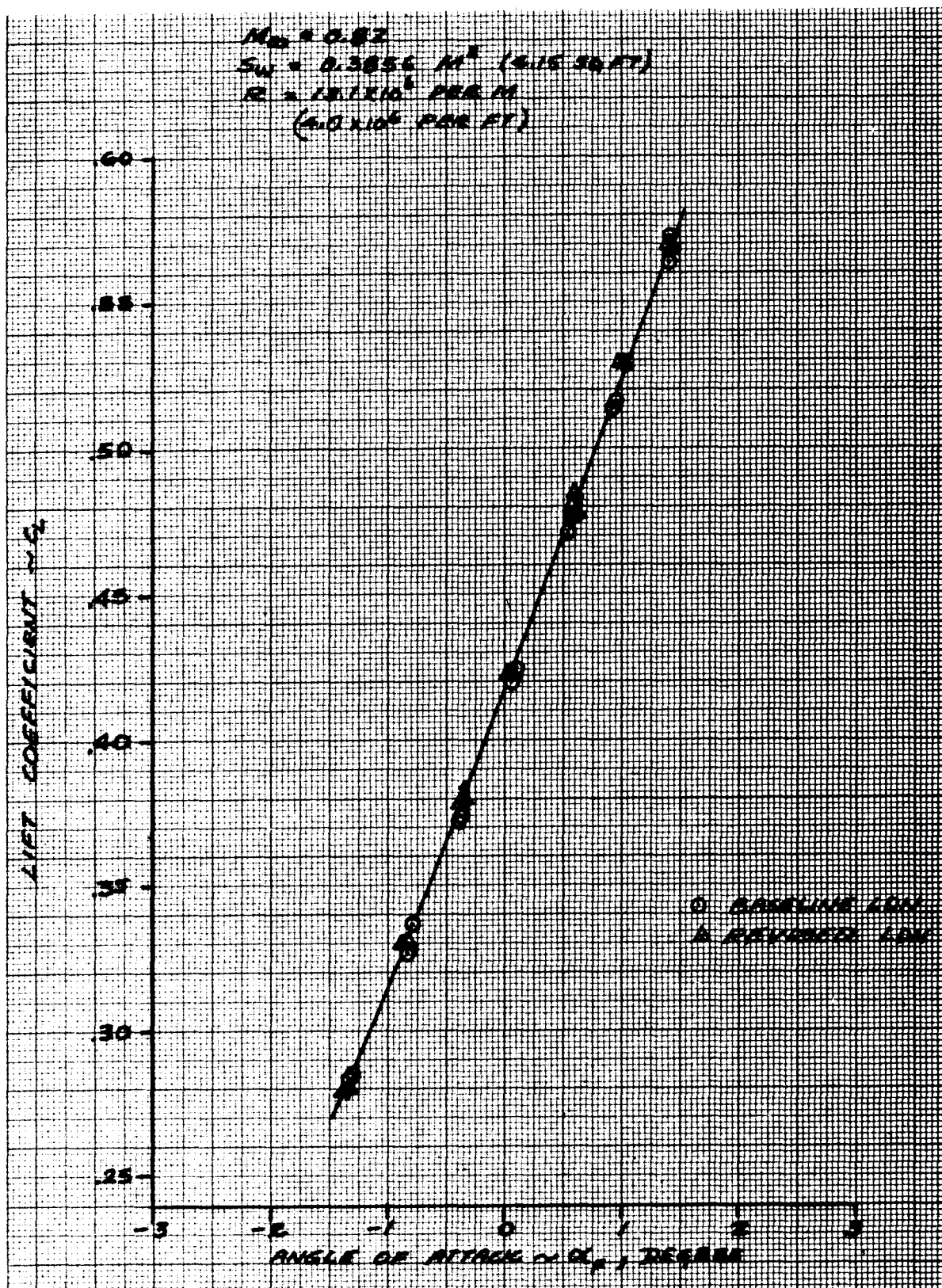


FIGURE 8. LIFT CURVE FOR BASELINE AND REVISED LDN ( $M_\infty = 0.82$ )

typical cruise conditions, the nacelle and pylon cause a loss in lift relative to the wing-body at the same angle of attack. The loss in lift measured during this test was in good agreement with the increment that was measured at Ames.

The measured incremental drag difference between the revised LDN and the baseline LDN is shown in Figure 9. The incremental drag is about two to four counts (three counts is approximately equal to one percent of airplane drag). The estimated increment due to the revised nacelle is about one count at tunnel conditions (internal and external drag). The estimated drag difference was calculated from conventional drag methods using the additional wetted area of the revised nacelle and the appropriate local dynamic pressures. No isolated force measurements were made. The difference between measured and estimated drag is not understood, in that there is no evidence of a flow separation or a significant lack of recovery on the nacelle or wing. While it is possible that the isolated nacelle drag is larger than estimated, it is more probable that the facility cannot accurately determine such small drag increments.

As previously explained, the need for a revised nacelle arises from requirements of internal flow-mixing performance with the CF6-50 engine. Such an installation might be appropriate for near-term application to the DC-10. For later versions of the aircraft, a derivative of the engine, identified as the CF6-80, is planned. The reduced length of the derivative would allow an LDN configuration with nearly the same length as the CF6-50 baseline LDN. It is concluded that the results of Reference 1 would be applicable to the derivative LDN.

After the Ames tests results were analyzed, there was concern that the pressure data measured in those tests might be optimistic. The basis for this concern was the lower severity of the pressures measured from the DC-10 production short-duct nacelle (SDN) model compared with those obtained from full-scale flight measurements. If this difference were valid and if the difference were applicable to the model measurements in the LDN test, then the LDN installation might turn out to be more critical in flight. The Ames data were adjusted to account for the difference between model and flight data, but the adjustment did not appear to invalidate the general conclusion that the interference drag of the LDN was small. However, the validity and cause of the difference remained unknown. The cause of the difference could have arisen from a measurement error for the SDN or from the manner in which the model was mounted. The Ames model fuselage was mounted on the tunnel floor, whereas at Calspan the floor boundary layer was isolated by a splitter plate. Previous Calspan measurements for the SDN had shown good agreement with the flight data.

A comparison of the channel pressures measured at Calspan with those measured at Ames for the baseline LDN is shown in Figure 10. The comparison is at 0.82 Mach number and 0.50 lift coefficient. The pressure data are in good agreement. On the basis of the comparison shown in this figure (other Mach numbers showed equally good agreement), it appears that the concern regarding the possibility of a more critical flight condition was unfounded. It can be concluded that the LDN channel pressures measured at Ames are representative of what might be expected in flight.

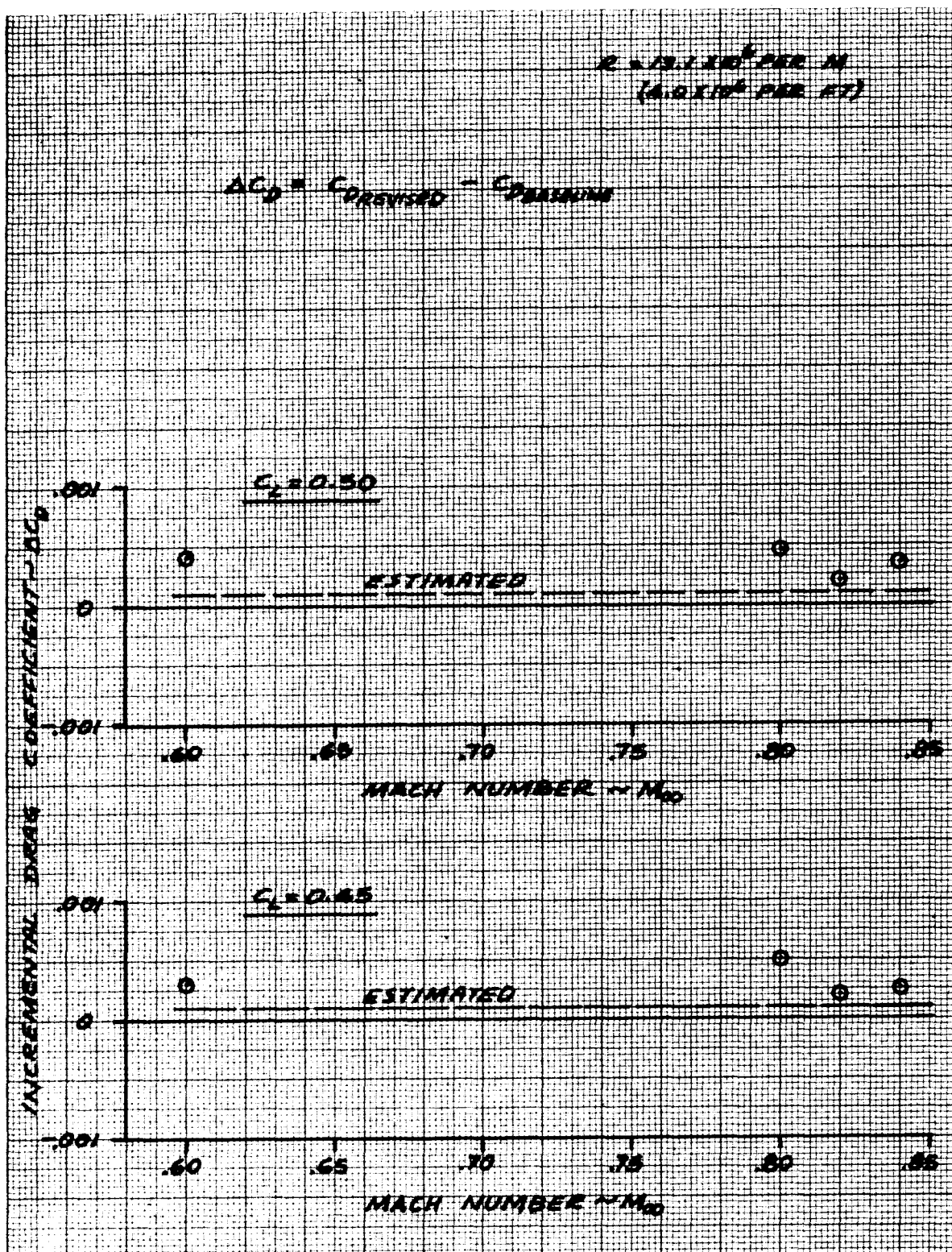


FIGURE 9. INCREMENTAL DRAG DUE TO REVISED LDN RELATIVE TO BASELINE LDN

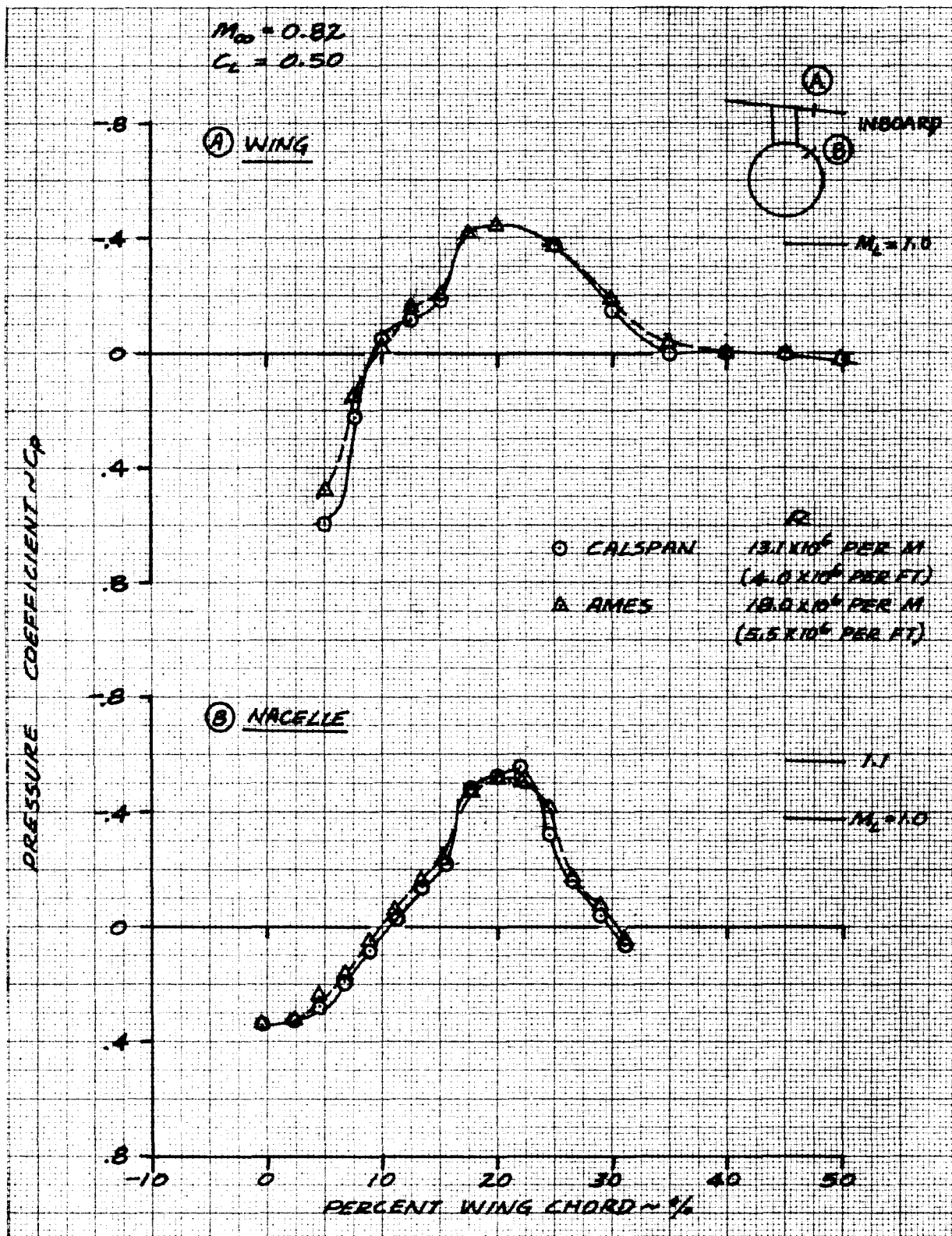


FIGURE 10. EFFECT OF LDN INSTALLATION ON INBOARD CHANNEL PRESSURES FOR  
 BASELINE LDN - COMPARISON OF CALSPAN WITH AMES  
 $(M_\infty = 0.82, C_L = 0.50)$



## CONCLUSIONS

A wind tunnel test to identify the effects of a revised LDN for the GE CF6-50 engine relative to the baseline LDN was conducted in the Calspan 8-foot transonic wind tunnel. The revised LDN incorporated a rearward extension of the afterbody to confer improved geometry for an internal mixer. The conclusions of the test are listed below.

1. The revised LDN had an appreciable effect on the channel pressure distributions, resulting in an increased peak channel Mach number of  $\Delta M_L \approx 0.10$  at typical cruise conditions. However, the pressure recovery on the nacelle afterbody was about the same for both nacelles.
2. The lift curves for both LDN configurations were the same.
3. The channel pressures measured at Calspan for the baseline LDN were in good agreement with those measured at Ames, thus dispelling the concern that the LDN pressures measured at Ames might be optimistic.
4. The incremental drag for the revised LDN was measured as two to four counts (three counts is approximately equal to one percent of the airplane drag), compared with the estimated increment of one count. However, this result may not be representative of the true incremental drag, since previous tests in this facility by Douglas have not been successful in determining small drag increments due to configuration changes.
5. The measured drag increment and the increased channel velocities for the revised nacelle shape are of sufficient concern to warrant consideration of pylon or nacelle changes designed to reduce the impact of the revised nacelle shape on the channel velocities and its potential attendant drag increase. An appropriate pylon change might be similar to the small fairing tested in EET Phase I.

For an LDN having the derivative CF6-80 engine, which is also suitable for the DC-10 aircraft, the geometry provisions for an improved internal mixer can be accommodated in the baseline nacelle shape representation of Reference 1. The results reported in that reference are therefore applicable in this case.



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